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THE ADDITION OF TRIM COILS TO THE TANDEM  
MIRROR EXPERIMENT UPGRADE (TMX-U)  
MAGNET SYSTEM TO IMPROVE THE MAGNETIC  
FIELD MAPPING

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THE ADDITION OF TRIM COILS TO THE TANDEM MIRROR EXPERIMENT MAGNET SYSTEM  
TO IMPROVE THE MAGNETIC FIELD MAPPING\*

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Abstract

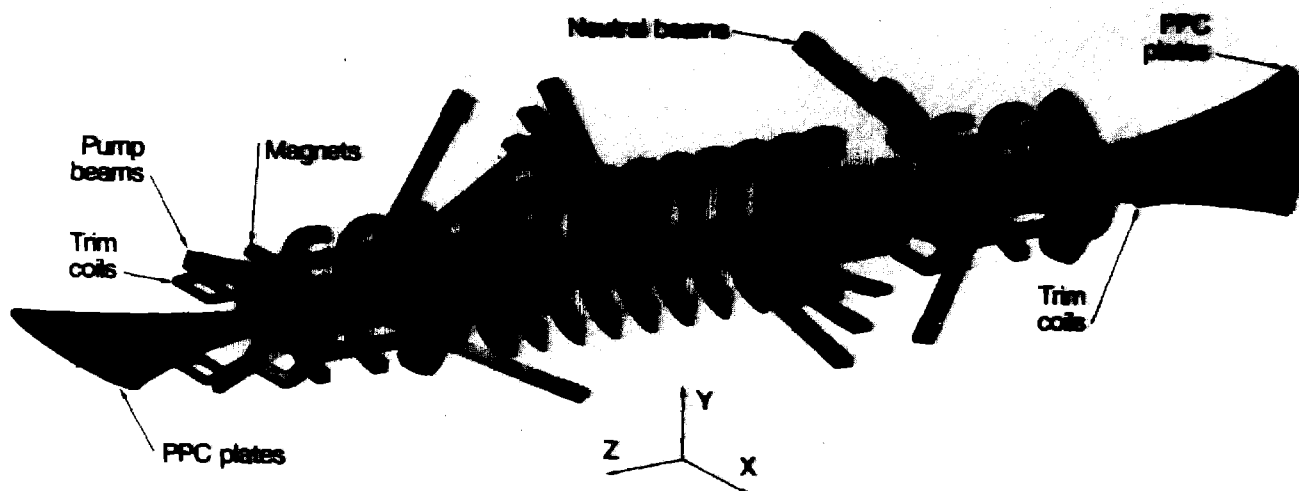
The mapping of the magnetic flux bundle from the center cell to the Plasma Potential Control plates (PPC) on the end fan of the Tandem Mirror Experiment Upgrade (TMX-U), was improved by the addition of trim coils (12,000 amp-turns) on each side of each end fan next to the pump beam magnetic shields. The coils' axes are oriented perpendicular to the machine centerline. These coils made the necessary corrections to the field-line mapping, while keeping the field in the nearby pump beam magnetic shield below the saturation threshold.

This paper briefly describes the problem, discusses the design as it evolved, and presents the results of the field testing. The disturbance to the field mapping and the appropriate corrections were determined using the code GFUN (a three dimensional electromagnetic field analysis code that includes the presence of permeable materials). The racetrack-shaped coils have dimensions of 1.5 feet by 3 feet and are powered by a renovated 600 kW Bart-Messing power supply controlled by the machine's magnet control system. The magnets were fabricated from polyimide-coated magnet wire. They are rated to 200°C, although in pulsed operation they rise only a few degrees centigrade. The coils are placed outside of the vacuum system and thus are considerably simpler than

the other machine magnets. The restraints are designed to withstand a force of 1000 pounds per coil and a turning moment of 1000 foot pounds. The calculated field strengths were verified on the machine by inserting a Hall probe along the axis. The perturbations to the neutral beam magnetic shields were also measured. A brief description of the improvement in the machine performance is also included.

Introduction

The pumping neutral beams, located outboard of the plug coils on each end of the TMX-U experiment (Fig. 1), have 1/4-inch- and 3/4-inch-thick carbon steel magnetic shields to bring the background field from a maximum value of 770 G down to about the 1 G that is required for proper neutral beam operation. However, this much high permeability material near the plasma perturbs the magnetic field outside of the outer mirror. These perturbations adversely affect the mapping of the field lines from the center cell to the contoured PPC plates on the end wall.[1] The addition of trim coils next to the shields improves the PPC plate mapping by sharply reducing the effect of the steel shields near the centerline of the machine. They also prevent the field lines from intersecting the cold liners.



**Fig. 1. TMX-U Upgrade with Pumping Beams, Trim Coils, PPC Plates**

## Analysis

The trim coils are modeled as 1.04-m by 0.51-m window-frame-shaped coils located next to the pump beam shields. The model shown in Figure 2 is from the GFUN code [2] that was used in their design. GFUN allows finite element modeling of the shields. Because of the limited number of available elements,

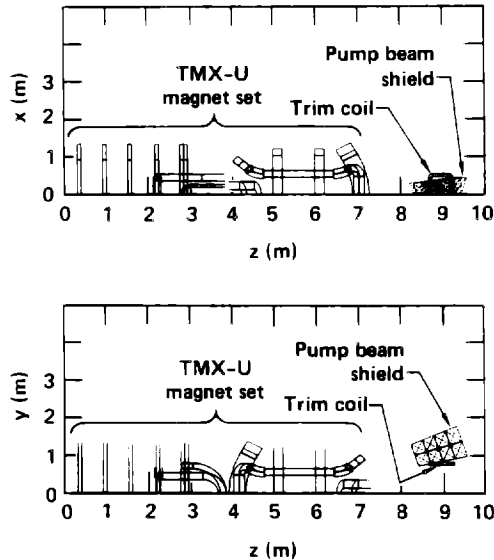


Figure 2. GFUN model TMX-U magnet set, pump beam shield, and trim coil

the shields were modeled as solid blocks of iron with volume-averaged permeabilities. Since the shields do not saturate (even with volume-averaged permeabilities), the model is valid for effects outside of the shields. Note that the shield and trim coil system is symmetric; there are two located on each end of the TMX-U magnet set. The fields through the two trim coils buck each other and add to the magnetic flux between the trim coils and the end wall.

The field line trajectories with and without the shields and trim coils are shown in Fig. 3, which is a cut in the y-z plane (narrow fan direction). The design current of 7200 amp-turns allows the 0.2-m plug field line to map from the plug minimum ( $z = 5.68$  m,  $y = 0.2$  m) to the same PPC plate location ( $z = 1.023$  m,  $y = 0.48$  m) as the unperturbed field lines. The trim coil also deflects the field line away from the cold liner.

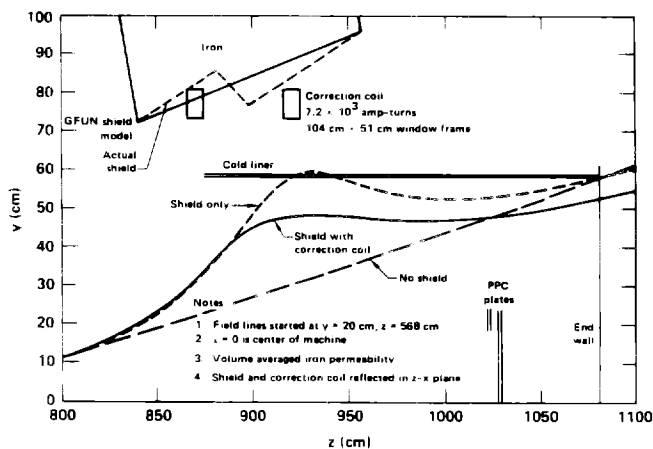


Figure 3. Cross section through end fan showing the field lines with and without shield and correction coil

The 0.1-m and 0.2-m plug radius flux bundles are mapped from the plug to the PPC plates (Figures 4-5). For comparison, the cross sections are shown with and without the shields and trim coils. The mapping deviation is acceptable.

The trim coils add to the flux carried by the shields in the region next to the trim coils and toward the center cell. This region was checked for possible saturation that would allow the field inside the shield to increase beyond the 1 to 2 G limit. Since GFUN has only enough elements to model the shield as a block of iron, this saturation check was done experimentally, and the fields inside were found to be acceptable.

These shield saturation tests were conducted concurrently with the magnet design. An available 4 inch diameter coil was placed next to a neutral beam magnetic shield in the same orientation that the trim coils would have. A survey within the magnetic shield with the magnet energized with a field of 125 G showed a small field increase near the arc chamber. The magnetic field increase is acceptable for this neutral beam operation. Later operation of the neutral beams with the trim coils installed and operated verified that the effect is not significant.

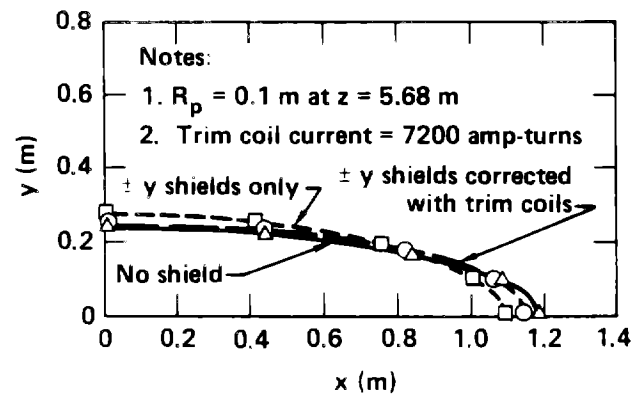


Figure 4. Comparison of the flux bundle at  $R_p = 0.1$  m in the plug for three cases: no magnetic shields, shield in position, and trim coils energized with shields in position.

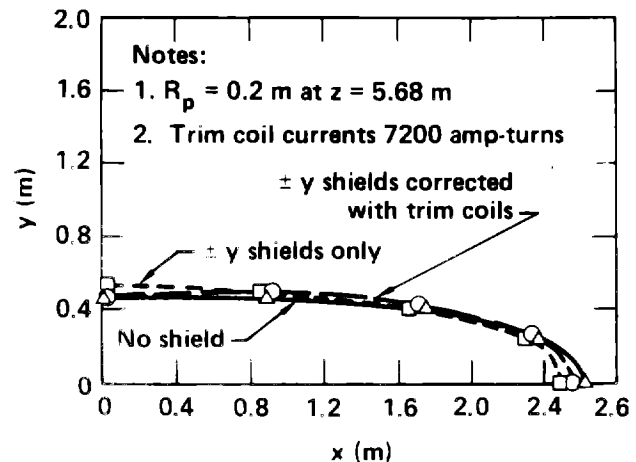


Figure 5. Comparison of the flux bundle beginning at  $R_p = 0.2$  m in the plug for three cases: no magnetic shields, shields in position, and trim coils energized with shields in position.

## Magnet System Design

The magnet system design was dominated by the need to quickly install the coils so that the plasma potential experiments could continue. This required the use of two existing 6-kW power supplies. The four required magnets were designed, fabricated, and installed in one month.

The coil geometry and the field intensity were dictated by the GFUN code. The size of the coils was limited by their location under the ribs of the vacuum vessel fan tank. Additional design criteria include the need to operate for the remaining life of the experiment, and the need to match the existing power supplies.

The cross-section of each of the eight coils is shown in Figure 6. It is a 64-turn coil arranged in an 8 x 8 cross section with a single row of copper tubing in the center for cooling. The conductor is AWG #4 copper magnet wire insulated with polyimide insulation with a continuous operation temperature rating of 200°C. The electrical insulation is rated at 1000 V to ground. The coil is cast into a monolithic structure using a EPON 815 epoxy with an Agent D curing agent. This is a long pot life, bulk curing agent widely used for moderate sized coils at Lawrence Livermore National Laboratory (LLNL). Alumina was added to the formulation to increase the thermal conductivity of the matrix. Although the coil is designed to operate under normal operating conditions without cooling water, a row of cooling

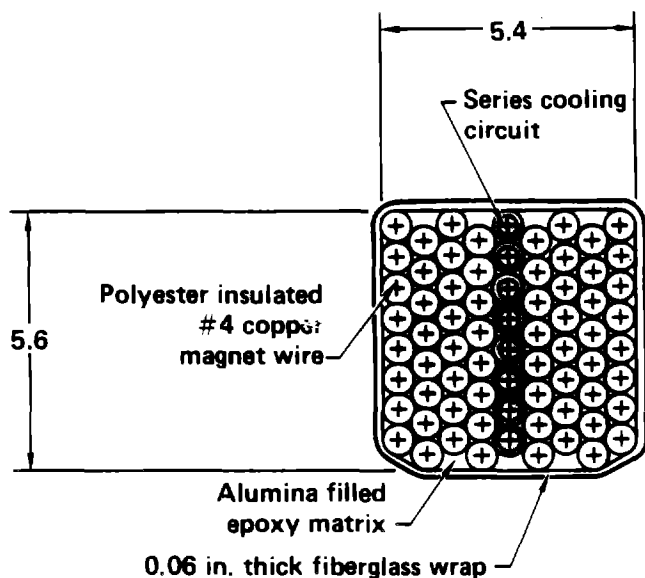


Figure 6 Trim coil cross section

tubes was easily added to the center of the coil to allow higher current operation if desired.

The conductor cross section was chosen to allow the delivery of 12,800 amp-turns (200 amps) from two each of coils in a series circuit with a single 6-kW power supply. In dry operation, the coils can dissipate a 4-second, 3-kW pulse every five minutes by rising to a peak temperature of 75°C. The largest fraction of the temperature rise occurs in the natural convection boundary layer (45°C). With the water cooling, the coil can be powered to 700 amps, but in this configuration the coils must be connected to larger power supplies.

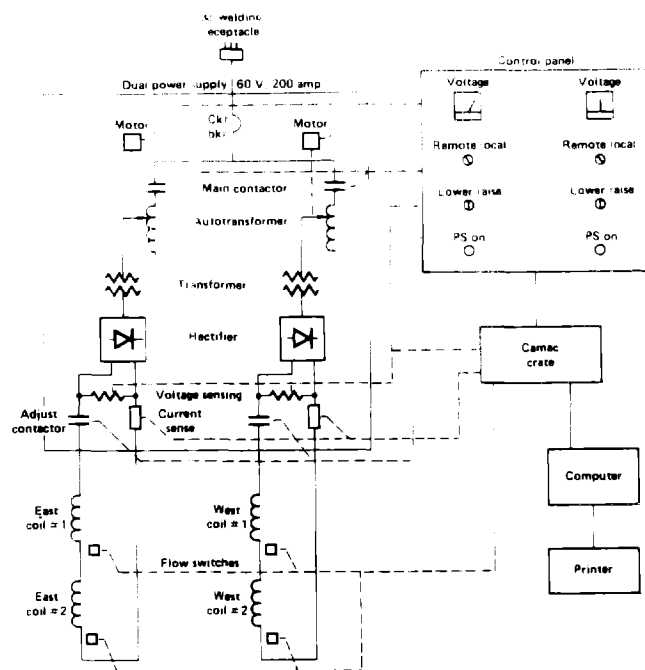


Figure 7 Trim coil power supply circuit

The power supply circuit is shown in Figure 7. The coils are controlled and protected by the same system as the rest of the TMX magnets. The protective circuit includes a hard wired, timed safety circuit; a software circuit comparing the resistance of circuit to the temperature of the coils; and a temperature sensor and flow meter on the exhaust side of each cooling circuit.

The trim coil system operated as predicted. The GFUN model was verified experimentally with Hall probe measurements taken near the centerline of the end fan after the trim coils were installed. For ease of measurement, the trim coils were run without the TMX-U magnet set, and their current was changed to make their fields additive. Table 1 lists the measured and calculated results. Due to symmetry,  $B_y$  and  $B_z$  should be zero. The results in Table 1 show them to be small. The calculated  $B_y$  is not zero due to small nonsymmetries in the shield finite element zoning. The measured and calculated values of  $B_x$  agree to within 2 G.

Table 1

Comparison of Experimental and GFUN Calculation Fields

z	Test	Test	Test	Calc.	Calc.	Calc.
m	$B_x$	$B_y$	$B_x$	$B_x$	$B_y$	$B_z$
	G	G	G	G	G	G
8.96				31.00	0.20	0.00
9.19	27.80			26.00	0.20	0.00
9.45	15.80		-0.80	14.70	0.10	0.00
9.70	7.00	1.70	-0.45	5.00	0.08	0.00
9.95	0.94	0.18	-0.08	1.10	0.05	0.00
10.21	-0.30	-0.15	0.06	-0.44	0.03	0.00
10.77	-0.30	-0.08	0.03	-0.82	0.01	0.00

## References

- [1] E. B. Hooper, Jr., Radial Transport Reduction in Tandem Mirrors Using End-Wall Boundary Conditions, UCRL 90639, Lawrence Livermore National Laboratory, November, 1985.
- [2] A. G. Armstrong, et. al., GFUN3D User Guide, Rutherford Laboratory, England, Rept. RL-76-029/A, November, 1976.